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Original Research Paper

Material development for a sustainable precast concrete block pavement

R. Bharathi Murugan [a,*], C. Natarajan [a], Shen-En Chen [b]

[a] Department of Civil Engineering, National Institute of Technology, Tiruchirappalli 620015, India

[b] Department of Civil and Environmental Engineering, University of North Carolina at Charlotte, Charlotte, NC 28223, USA

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ABSTRACT

Portland cement concrete (PCC) and asphalt concrete (AC) are the most common roadway and highway construction materials which are more suitable for continuous slab pavements. The durability of these materials is highly dependent on construction quality and techniques, and both materials are difficult to repair. Heavy rain storms in India have recently revealed several roadway pavement failures and resulted in significant repair costs. Interlocking block type pavements are simpler to construct and maintain than both PCC and AC pavements but, have only been used for slower traffic roads due to weak interlocking at the joints. To improve the quality of block pavements, blocks made of PCC with waste tire crumb rubber partially replacing river sand (fine aggregate) are suggested. The joint interlocks can be further improved by modifying the block geometry. The material is completely recycled and is deemed more superior than concrete pavements when repair and construction techniques and costs are concerned. This paper presents the material characterization of Rubberized Concrete Blocks (RCBs) using crumb rubber particle size ranging from 0.075 mm to 4.75 mm to partially replace the fine aggregates. It also discusses the advantages of RCB over continuous material pavements.

1. Introduction

Conventional modes of roadway and highway pavement construction utilize predominantly in-situ, large dimension and slab-based techniques with either Portland cement concrete or hot mixed asphalt concrete (AC). Due to the wear, tear and abuses of daily traffic, paved roads experience usage damages and require constant maintenance. For example, based on the 2010 capital spending estimate, the US spends \$65.3–\$86.3 billion annually for highway condition maintenance (US DOT, 2013). Furthermore, the maintenance of roadways require extended traffic closure periods to complete the patching, overlaying, cutting and curing of materials involved, all resulting in additional financial

* *Corresponding author*. Tel.: +91 9488024542.

E-mail address: rbmmecivil@gmail.com (R.B. Murugan).

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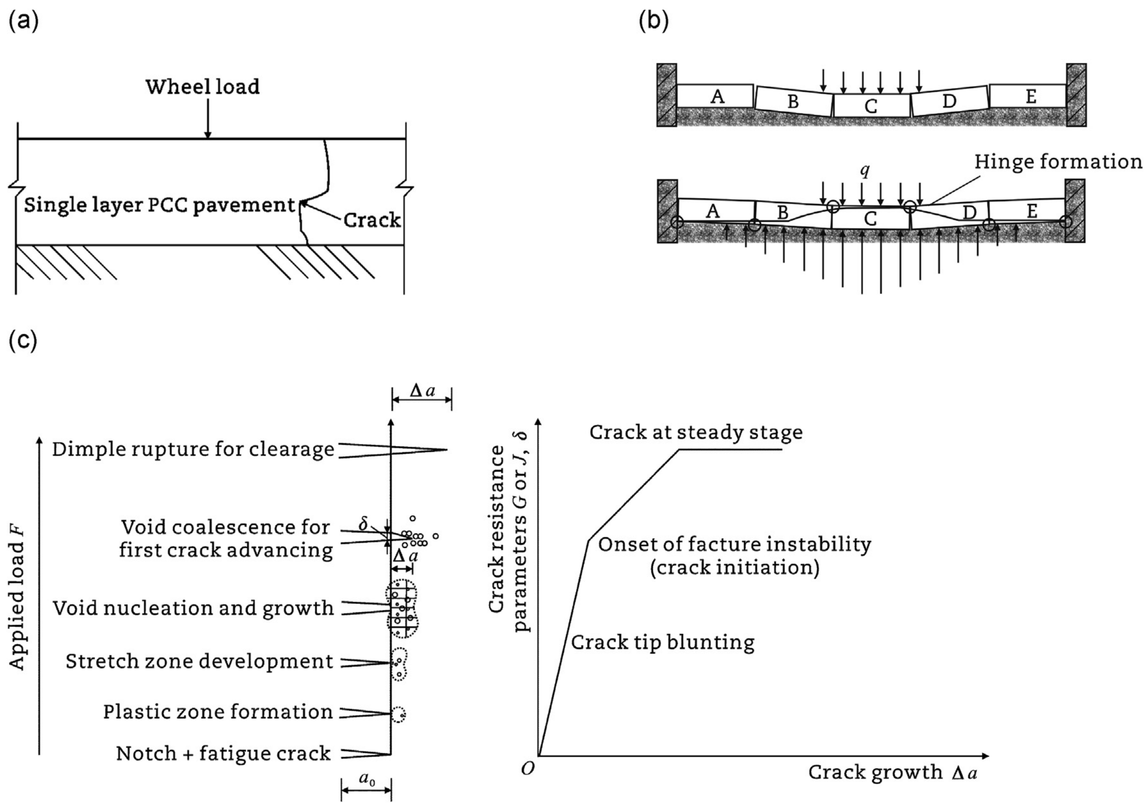

Fig. 1 – Failure modes of different pavements. (a) PCC pavement. (b) Concrete block pavement (Soutsos et al., 2011). (c) AC pavement (Tang, 2014).

losses. The key disadvantages of conventional roadway in-situ construction and maintenance are inconveniences to drivers and additional costs associated with extensive site operations. In addition, there is also the seasonal constraint to on-site constructions such as concrete curing or hot mix asphalt placement during low temperatures, that can result in sub-standard products. An alternative pavement technology is the use of block pavements. Despite advances in concrete block pavement technologies, the use of concrete block pavement (CBP) remains limited and must be promoted.

State-of-the-art reviews of CBP technologies indicate that modern CBPs' have excellent engineering properties and low life cycle costs. They are easy to construct and maintain, and have a very good esthetic appearance as compared to conventional pavements (i.e., concrete and asphalt). Additionally CPB's can be easily replaced, thus minimizing the waste of materials and time for construction. This last advantage makes CPB's more sustainable than conventional pavements.

The durability of CPB is mainly dependent on the quality and strength of the paving block. However, the block–block interface conditions are also critical to the overall performance of the pavement. The paving blocks can be produced in different grades of concrete, shapes and sizes (Shackel, 1990). Several standards and specifications, such as the Indian Standards (Bureau of Indian Standards, 2006), the British Standards (BS EN 1338:2003) (British Standards Institution, 2003), the ASTM C936/C936M (ASTM, 2015), are available for the detailed definition and basic requirements of the paving blocks. In earlier global standardization efforts, Houben et al. (1984) gave a comprehensive review of all published standards, which documented block thickness of 140 mm in some cases.

For typical applications, the small element of precast paving unit is used as a surface course and the bedding sand provides a more flexible response compared to conventional pavements (Singh et al., 2012). Thus, the following factors can influence the structural performance of CBP: (1) paving blocks (i.e., shape, size, thickness and laying pattern); (2) bedding sand (i.e., thickness, grading, angularity and moisture content); (3) base and sub-base (i.e., material type and thickness); and (4) sub-grade (i.e., material type and strength) (Soutsos et al., 2011). Joints can be filled with sand to enhance the interface friction. Polymer filler material can be used to stabilize the joint sand and reduce water infiltration.

Loading frequency and scenarios are also critical to the durability of block pavements. The standard IS 15658:2006 clearly indicates that the strength and thickness of paving blocks are decided based on the traffic volume. For high volume traffic roads, there is a need to carry large amounts of load, thus requiring stronger and thicker paving blocks. The sub-base and bedding sand thickness are selected based on required bearing capacity of the base course design. For base course with lower bearing capacity, the required sub-base and bedding sand materials would be more.

Manufactured paving blocks have a high compressive strength, but they can still fail during heavy traffic loads due to weaknesses and result in spalling and cracks. Therefore, CPBs require high flexural strength and toughness to sustain a heavy traffic load. However, it is difficult to improve the flexural capacity of conventional concrete block without modifying its material properties. Therefore, there is a need to modify conventional concrete ingredients to improve the toughness of the paving block. In this paper, waste tire crumb rubber mixed with conventional concrete is suggested as a sustainable way to improve block toughness. The result is a Rubberized Concrete Block Pavement (RCBP), which has been shown to have a good resistance to cracking and fracture as compared to conventional concrete (Li et al., 2004; Ling et al., 2009b).

Toughness is a parameter that describes the fracture response at a sudden impact load. The toughness of paving blocks can help quantify their resisting properties to cracking induced by frequent wheel impacts. In this study, crack resistance is evaluated based on the impact test suggested by ACI 544. 2R-89. As seen from the test results collected, the impact energy of the paving block is calculated for the first cracking load and the load at complete failure. The ductility index is also measured from the first crack and failure impact energy.

The authors of this paper focus on fundamental studies of concrete material modification with the partial replacement of fine aggregates with crumb rubber from waste tires. Crumb rubber is made of shredded waste tires, and, is thus a waste reduction technique to sustains the living environment. Waste tire utilization has been studied as early as the 1990s (Siddique and Naik, 2004). The main advantages of crumb rubber utilization in concrete include lower density, higher impact and toughness resistance, enhanced ductility, and better sound insulation. However, waste tires are very difficult to handle because they are not naturally biodegradable (El-Gammal et al., 2010; Issa and Salem, 2013; Khaloo et al., 2008). Out of the three conventional methods of waste tire handling (i.e., reuse, burning and dumping), the burning of waste tires results in large amounts of CO, NO_x and SO_x emissions. Dumping waste tires can also create serious land hazard and settlement effects (EPA, 1999).

Previous efforts to use waste tire for construction applications involved shredding the waste tires into small particles, then using them as concrete aggregate replacements (Siddique and Naik, 2004). In this paper, the authors explore the possible use of waste tire crumb rubber as a partial replacement of fine aggregates by volume in pavement blocks. The study focuses on the use of rubberized concrete blocks in roadway pavement applications.

2. Damage mechanisms of pavements

Fig. 1 demonstrates the different conceptual failure modes involved in PCC pavement, AC pavement and CBP pavements. In contrast to both PCC and AC pavements, block pavements involve joint action, which may result in hinge formation. This presents the blocks with stress release and preserves their integrity. AC pavement behavior is significantly affected by surface temperature due to solar radiation and ambient conditions, where as such thermal effects are less pronounced in PCC and CBP pavements. RCBP and CBP pavements share similar damage mechanisms. Both AC pavements and RCBP may involve crack tip blunting due to the presence of rubberized material (i.e., rubber in tire and bituminous material in asphalt). As seen in Fig. 1(b), concrete block pavement can be designed to optimize the flexural behavior of the block pavement system and moderate interactions between block and joint behaviors.

Important aspects of rubberized concrete are possible strain softening and fracture arrest mechanisms due to the presence of rubber shreds within the concrete material which is not shown in Fig. 1. A previous study has shown that rubber shreds can reduce the plastic shrinkage cracking of concrete, which can significantly enhance its durability (Twumasi-Boakye, 2014). The proportioning of amount of rubber shreds can help reduce shrinkage behavior and optimize material performance. This study characterizes the block behavior with different proportions of rubber shred mix.

3. Materials and methods

3.1. Materials

Ordinary Portland cement 53 grade (OPC 53) conforming to IS 12269:1987 is used throughout this study (Bureau of Indian Standards, 1987). The cement properties were determined, and test results are summarized in Table 1. River sand was used as the original fine aggregate. River sand properties are defined per IS 383:1970, where the specific gravity was found to be 2.65 and fineness modulus of 2.45 was used (Bureau of Indian Standards, 1970). Crushed granite stones with a maximum size of 20 mm, specific gravity of 2.63 and fineness modulus of 7.2 were used as coarse aggregates. The shredding of waste tires produced crumb rubber particles that passed through a sieve size of 4.75 mm and was determined to have specific gravity of 0.689.

3.2. Mix proportion

UNI-Paver 50 mm thick paving blocks were manufactured at a local plant for compressive strength and flexural strength tests. To determine the static strength and moduli parameters, cylinders with a 150 mm diameter and 300 mm height were cast. An M20 grade concrete with a cement, fine aggregate and coarse aggregate ratio of 1:1.89:2.88 and water to

Table 1 – Cement properties.

Sl. No.	Properties	Results	IS 12269:1987 requirements
1	Normal consistency	31%	–
2	Specific gravity	3.14	–
3	Initial setting time (min)	65	Not <30
	Final setting time (min)	280	Not >600
4	Fineness (m^2/kg)	320	225
5	Compressive strength		
	7 d (N/mm^2)	38.60	37.00
	28 d (N/mm^2)	56.96	53.00

Table 2 – Concrete mix design.

Sl. No.	Mix ID	Crumb rubber replacement (%)	Mix ratio C:FA:CA:CR	Slump (mm)
1	R0	Control mix	1:1.89:2.88:0.00	48
2	R5	5% FA replaced by CR	1:1.78:2.88:0.09	50
3	R10	10% FA replaced by CR	1:1.71:2.88:0.18	52
4	R15	15% FA replaced by CR	1:1.62:2.88:0.27	56
5	R20	20% FA replaced by CR	1:1.53:2.88:0.36	61
6	R25	25% FA replaced by CR	1:1.44:2.88:0.45	69

Note: C: Cement; FA: Fine aggregate; CA: Coarse aggregate; CR: Crumb rubber.

cement ratio of 0.5 were used as the control. Table 2 shows the concrete mix design used in this study.

3.3. Test methods

In this paper, waste tire fines are mixed in PCC blocks with different percentage replacements of fine aggregates (i.e., 5%, 10%, 15%, 20% and 25%). The blocks were then tested for compressive strength, flexural strength, static modulus of elasticity and impact energy. The results comparing concrete with crumb rubber and normal concrete without rubber are presented in the following.

The compressive strength and flexural strength test was performed in accordance with IS 15658:2006 and the static modulus of elasticity test was performed in accordance with IS 456:2000 (Bureau of Indian Standards, 2000, 2006). The IS 456:2000 recommends an empirical relation between the static modulus of elasticity and compressive strength of concrete, expressed below as Eq. (1).

$$E_c = 5000\sqrt{f_{ck}} \tag{1}$$

where E_c is static modulus of elasticity in MPa, f_{ck} is characteristic compressive strength of concrete at 28 d in MPa. IS 456:2000 further suggests that the flexural strength, f_r, of concrete can be defined as Eq. (2).

$$f_r = 0.7\sqrt{f_{ck}} \tag{2}$$

Guidelines from ACI committee suggest that the impact energy from a load can be determined via the free fall of a drop weight onto the center of at paving block (ACI, 1999). A 4.54 kg weight was lifted to 0.457 m above the specimen and then released. The drop weight impact testing machine is shown in Fig. 2. The weight was dropped repeatedly, and the blows required to produce the first visible crack and complete failure of the specimens were noted. The impact energy is then calculated for each paving block using the following equation.

$$U = \frac{nmv^2}{2} \tag{3}$$

$$v = \sqrt{2(0.9g)h}$$

where U is impact energy, n is number of blows, m is weight of the hammer (4.54 kg), v is drop weight hammer velocity, g is gravitational acceleration, and h is drop height (0.457 m). A factor of 0.9 was used to account for the effect of air resistance and friction between the lifting weight and guided rails.

4. Material characterization results

4.1. Workability

Table 2 shows that the addition of crumb rubber increased the concrete's slump, indicating that the crumb rubber improved the workability of the concrete material. Since crumb rubber does not absorb water as compared to river sand, less water is needed for rubberized concrete to achieve good workability.

4.2. Compressive strength

The 28-day compressive strength, on the other hand, reduced with increasing crumb rubber replacement. Fig. 3 shows the decreasing strength versus increasing rubber replacement. This observation is consistent with several previous studies. 25% of rubber replacement represents a strength reduction of nearly 50%. The decrease in 28-day compressive strength of concrete with 5%, 10%, 15%, 20% and 25% waste tire crumb rubber was observed to be 7.85%, 13.34%, 21.92%, 29.90% and 46.44%, respectively, when compared to normal concrete without rubber replacement. The strength reduction due to crumb rubber addition may result from the fact that at first the rubber particles are much softer than the cement paste, resulting in rapid crack propagation around the rubber particles. This leads to failure in the rubber-cement matrix. Since rubber particles have more air content, they can increase the voids within the concrete and decrease the compressive strength of the paving block (Al-Mutairi et al., 2010; Guneyisi et al., 2004; Khatib and Bayomy, 1999).

4.3. Modulus of elasticity

To determine the rubber crump replacement effect on the Young's modulus, a value is computed from Eq. (1) and compared to the test results, which are shown in Fig. 4. The modulus for normal concrete is 29.43 MPa at 28 d, and the modulus decreases with increasing rubber content. Fig. 4 clearly shows that the measured moduli of elasticity are lower than the calculated values. Generally, normal concrete is more brittle when the modulus of elasticity is higher, and concrete mixed with a large volume of rubber is more ductile or flexible when the modulus of elasticity values are lower (Ling et al., 2009a). Therefore, it is proven that the addition of a low volume of crumb rubber into concrete notably increases the modulus of elasticity.

4.4. Flexural strength

A comparison of flexural strength and the computed values from Eq. (2) is shown in Fig. 5, where the experimental results peak at 5.2 MPa for R15 rubber replacement concrete. The improvement in flexural strength is limited to relatively small amounts of rubber crumb. In general, normal concrete is more brittle with a higher modulus of elasticity when

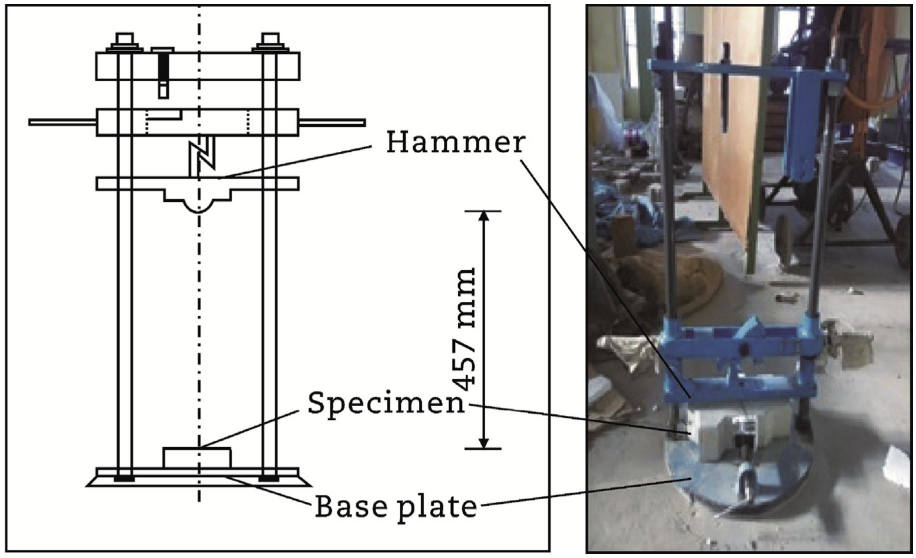

Fig. 2 – Impact testing machine.

compared to rubberized concrete mixed with large volumes of rubber, thus demonstrating a more flexible behavior (Ling et al., 2009a). However, empirical results according to IS 456:2000 show a consistent decreasing flexural strength with increasing rubber replacement contents, which contradicts the experimental results.

The authors believe that the flexural strength increase of RCB concrete demonstrates a possible bridging of rubber within the fracture zone, resulting in the arrest of fracture propagation. This phenomenon is described as "strain hardening" in fiber-reinforced concrete under tension, where the tensile behavior has demonstrated the fiber bridging within propagating cracks (Fantilli et al., 2009). Soranakom and Mobasher (2008)describe the post-crack flexural responses of fiber-reinforced concrete as "deflection softening" or "deflection hardening" because of the effective activation of tensile responses within the embedded fiber bridging, which is a function of the amount of fiber and the anchor strength of the fibers. The material characterization tests performed in this study demonstrate the flexural performance of RCB material, validating earlier speculation that block pavements using RCB can benefit from both the joint interaction and flexural strength of individual blocks.

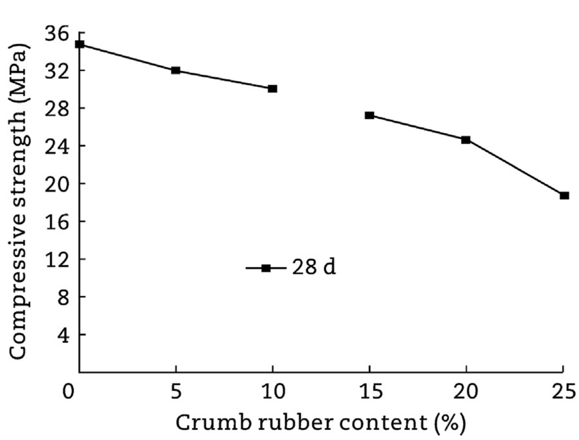

Fig. 3 – Compressive strength as a function of crumb rubber replacement.

4.5. *Impact energy*

The number of blows required to produce the first visible crack and complete failure for each type of paving block are presented in Table 3. Based on the number of blows the first crack impact energy and failure impact energy were calculated using Eq. (3) and plotted in Fig. 6. Compared to conventional concrete paving blocks, the first crack impact energy increased by 34.48%, 51.23%, 71.92%, 91.62% and 112.31%. The failure impact energy increased by 35.81%, 53.02%, 74.88%, 96.27% and 118.14%–5%, 10%, 15%, 20% and 25% of sand replaced by crumb rubber by volume, respectively.

With an increasing replacement percentage of shredded rubber, there is an increase in the impact energy of paving blocks, which is observed by other researchers such as Nili and Afroughsabet (2010), Yildirim et al. (2010), and Al-Tayeb et al. (2012). This trend holds true for both impact energies at first crack and at failure. The impact resistance of R25 is approximately twice that of R0 because crumb rubber absorbs more energy. This proves that rubber acts as a fiber and an effective crack arrestor, when an impact load is encountered. Thus plain concrete exhibits an early brittle failure when compared to fiber reinforced concrete which shows better ductile properties (Swamy and Jojagha, 1982). The failure mode of concrete depends on the cement matrix strength, aggregate strength and bond strength of the fiber with aggregate matrix.

4.6. *Ductility index*

There are different definitions for ductility index including one based on displacement measurements (Maghsoudi and Bengar, 2011). In this case, the ductility index is defined as

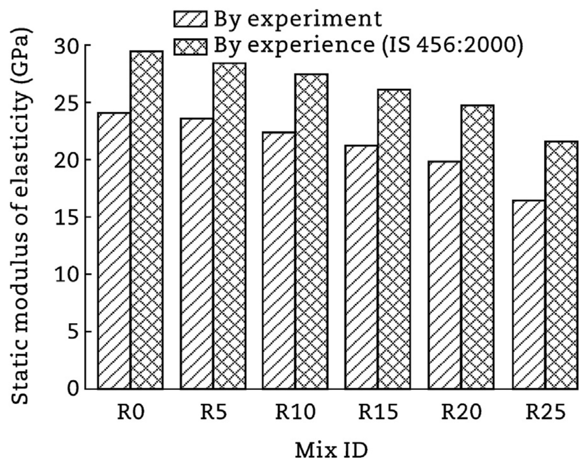

Fig. 4 – Static modulus of elasticity as a function of crumb rubber replacement.

the ratio of energy absorbed at failure to energy absorbed at first crack (Senthilvadivel et al., 2014). Fig. 7 shows variations in the ductility index of the wet cast paving blocks based on the crumb rubber replacements at various percentages. An increase in the ductility index value is observed when the percentage of crumb rubber in concrete mix increases. The percentages of sand replacement by crumb rubber (i.e., 5%, 10%, 15%, 20% and 25%) and the associated increases within the ductility index are 0.93%, 1.16%, 1.82%, 2.3% and 2.94%, respectively.

5. Discussions

A modified block response diagram is shown in Fig. 8 to demonstrate the micro-macro behavior of the likely moderation of block flexural responses and joint interlocking (hinge formation) mechanisms that resist over-bearing wheel loads. As shown in Fig. 8, the block/joint system provides a more uniform response against wheel

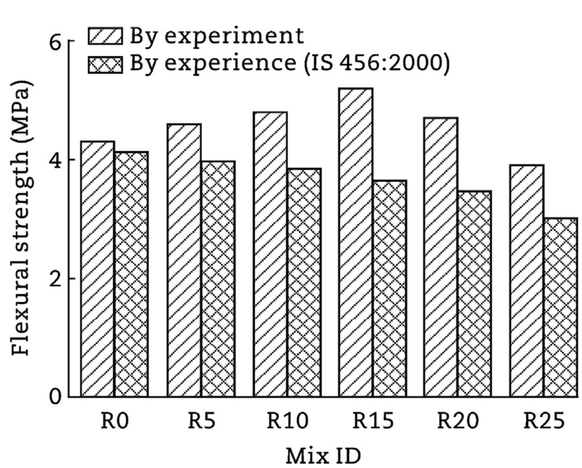

Fig. 5 – Flexural strength as a function of crumb rubber replacement.

loads with flexural hardening, and, at the same time, allows block separation at the ultimate load. Thus, a stronger response system is created using RCB's.

The current study only involves the testing of a single block element and does not accurately reflect the block–block-base interactions. Fig. 8 shows that the flexural response of the loaded individual block may lie opposite to the formation of the joint hinge, resulting in reduced stress at the joints. This mechanism is missing in continuous slab pavements and further proves the advantage of using blocked pavements in roadway loading. However, such tests require multiple block elements and are beyond the scope of this paper.

Additional enhancements to improve the impact resistance of pavement blocks, including the placement of black toppings on block pavements have also been introduced for airplane runways, which can also be considered for highway and roadway applications.

6. Summary and conclusions

This paper discusses a series of tests conducted to characterize concrete pavement blocks made with partial replacement of fine aggregates with waste rubber in the form of fine shredded crumbs. The tests conducted include strength tests and determinations of the modulus of elasticity and compressive and flexural strengths. Comparisons to conventional concrete blocks include derived parameters, such as the impact energy and ductility index. The test results support the initial assumption that rubberized concrete pavement blocks have superior toughness and strength compared to conventional concrete blocks. These blocks help mechanize the combined load bearing mechanisms that combine the hinge formation at joints and flexural bending of blocks. Observations from this study are summarized as follows.

- A series of tests investigate the behavior of concrete containing fine waste tire crumb rubber. The following conclusions are drawn based on the test results of this study, which show that there is an increase in slump values when crumb rubber content increases up to 25%. This means that the workability of rubberized concrete improves due to the addition of rubber crumbs and is acceptable in terms of the ease of handling, the placing and finishing of wet concrete as compared to normal concrete.
- Compressive strength is reduced with increasing rubber content, and the static modulus of elasticity of rubberized concrete is lower than normal concrete. However, the flexural strength of concrete increases up to 15% of the crumb rubber replacement. When the percentage of crumb rubber replacement increases over 15%, the flexural strength begins to decrease. An explanation may be based on tension strain hardening.
- If the suggested fracture arrest by the embedded rubber crumb/fiber, then the integration of flexural hardening and joint interlocking would make RCBP a superior roadway pavement system. Future studies should focus on demonstrating the global behaviors of a block pavement system with joint response monitoring.

Table 3 – Impact test results for plain and rubber mixed concrete.

Mix ID	No. of blows		Average no. of blows		Impact energy (J)		Average impact energy (J)		Ductility index	Average ductility index
	First crack	Failure	First crack	Failure	First crack (N_1)	Failure (N_2)	First crack	First crack	N_2/N_1	Average of N_2/N_1
R0	22	25	24.2	25.6	399.96	454.50	439.96	465.41	1.136	1.059
	23	25			418.14	454.50			1.086	
	26	27			472.68	490.86			1.038	
	22	22			399.96	399.45			1.000	
	28	29			509.04	527.22			1.035	
R5	39	41	38.2	41.4	709.02	745.38	694.48	752.66	1.051	1.085
	36	42			654.48	763.56			1.166	
	38	43			690.84	781.74			1.131	
	38	40			690.84	727.20			1.052	
	40	41			727.20	745.38			1.025	
R10	45	48	45.6	49.6	818.10	872.64	829.01	901.73	1.066	1.091
	48	49			872.64	890.82			1.020	
	46	48			836.28	872.64			1.043	
	47	49			854.46	890.82			1.042	
	42	54			763.56	981.73			1.285	
R15	51	56	52.6	58.0	927.19	1018.09	956.27	1054.45	1.098	1.102
	52	57			945.37	1036.27			1.096	
	54	62			981.73	1127.17			1.148	
	56	60			1018.01	1090.81			1.071	
	50	55			909.01	999.91			1.100	
R20	59	66	59.2	65.4	1072.63	1199.89	1076.26	1188.98	1.118	1.104
	60	65			1090.81	1181.71			1.083	
	62	69			1127.17	1254.43			1.112	
	58	64			1054.45	1163.53			1.103	
	57	63			1036.27	1145.35			1.105	
R25	63	70	63.8	70.8	1145.35	1272.61	1159.89	1287.15	1.111	1.109
	65	72			1181.71	1308.97			1.107	
	66	73			1199.89	1327.15			1.106	
	64	70			1163.53	1272.61			1.093	
	61	69			1108.99	1254.43			1.131	

- The impact resistance of the paving blocks was calculated in two stages: (i) first cracks impact resistance and (ii) failure impact resistance. Both stages of impact resistance were increased by the replacement of sand with crumb rubber up to 25% by volume of sand. The ductility index also increased when the crumb rubber content increased up to 25%.
- The incorporation of rubber content to concrete, changes, the failure pattern from a brittle mode to ductile mode,

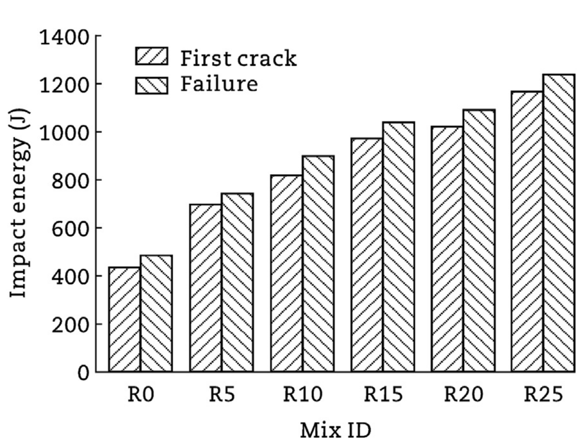

Fig. 6 – Impact energy of paving block.

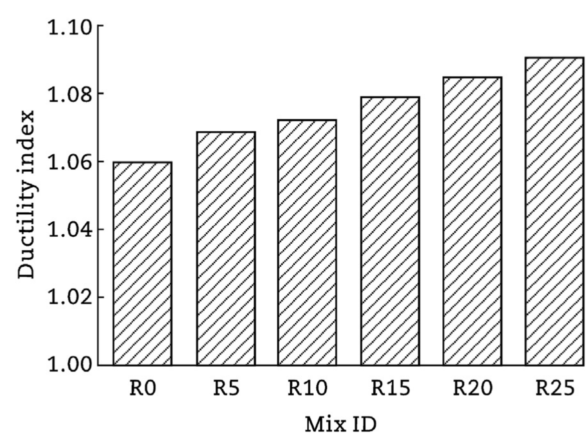

Fig. 7 – Ductility index of paving block.

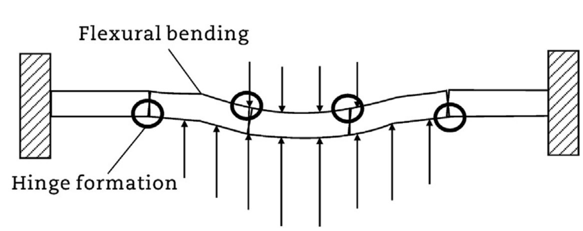

Fig. 8 – Flexural hardening and joint interlock in the load bearing mechanism of RCBP.

which displays the beneficial effects of Portland cement block with crumb rubber, used in absorbing vibrations.

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R. Bharathi Murugan holds a M. E (Structural Engineering), is pursuing his PhD at National Institute of Technology, Tiruchirappalli, Tamil Nadu, India. His research interests include special concretes, sustainable construction materials, pavement materials and utilization of waste materials in concrete.

Dr. C. Natarajan holds PhD degrees in civil engineering from IIT Madras, India. He is a professor in the Department of Civil Engineering at National Institute of Technology, Tiruchirappalli, Tamil Nadu, India. His research interests pertain to the domains of forensic investigation, size effects on beam, traditional structures, corrosion resistance in concrete and pavement materials. His publications in these areas are well cited.

Dr. Shen-En Chen holds PhD degrees in civil engineering from West Virginia University, USA. He is a professor in the Department of Civil and Environmental Engineering at University of North Carolina at Charlotte, USA. His research interests pertain to the domains of power transmission structures, carbon storage in geological formations, remote sensing for bridge monitoring and forensic investigation. His publications in these areas are well cited.